

# Pair annihilation and radio emission from galactic jet sources: The case of Nova Muscae

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## ABSTRACT

In the hard X-ray spectra of some X-ray binaries line features at around 500 keV are detected. We interpret these as arising from pair annihilation in relativistic outflows leading to a significant Doppler shift of the lines' frequencies. We show how this can be used to accurately determine the bulk velocity and orientation to the line of sight of the outflows. Constraints on the energy requirements of such outflows are also derived. Furthermore, we show that a small fraction of pairs escaping the annihilation region may give rise to the radio synchrotron emission observed in some of these objects. We apply these ideas to the hard X-ray and radio observations of Nova Muscae 1991. In this object, the energy requirements seem to rule out a large proton fraction in the outflows.

**Key words:** line: formation — plasmas — radiation mechanisms: non-thermal — stars: binaries: close — stars: individual: GRS 1124–684 — radio continuum: stars

## 1 INTRODUCTION

It has been known for some time now that a handful of Galactic X-ray transients has exhibited radio jets. The first X-ray binary for which a kinematic model involving radio jets was proposed to explain its bizarre observed spectrum was SS 433 in 1979 (Abell & Margon 1979). Subsequently, in 1994, apparent superluminal motion of ejected material was observed for the first time in our Galaxy from GRS 1915+105 (Mirabel & Rodríguez 1994). The velocity of the ejecta was estimated to be  $0.92c$  for an assumed distance of 12.5 kpc. Since that first discovery, four other *transients* have shown apparent superluminal motion: GRO J1655–40 (Hjellming & Rupen 1994; Tingay et al. 1995); XTE J1748–288 (Rupen, Hjellming & Mioduszewski 1998; V4641 Sgr (Hjellming et al. 2000); and XTE J1550–564 (Hannikainen et al. 2001).

In addition to the transient jet sources, there has also been evidence of steady compact radio jets during the low hard state of Galactic black hole candidate X-ray binaries from, for example, Cyg X-1 (Stirling et al. 2001) and 1E 1740.7–2942, or “The Great Annihilator” (e.g. Mirabel et al. 1992; see Fender 2001 for a full review on radio jets from X-ray binaries in the low hard state). The presence of jets in X-ray binaries gives rise to radio emission and in this paper we will take the observation of radio emission to indicate the presence of jets. Note however, that in the absence of resolved radio observations, this emission may also stem from other regions within the source.

The composition of the jets, either electron-positron or electron-proton plasma, is still not fully established. For example,

Gliozzi, Bodo & Ghisellini (1999) investigated the role of electron-positron pairs (amongst other possibilities) as energy carriers from the inner jet regions, and have excluded a pair plasma as a viable possibility. They argue that either hot or cold pairs cannot survive the annihilation.

In this paper we propose that the annihilation line features observed in the hard X-ray spectra of some X-ray transients arise from pairs in a bipolar outflow. At the time of annihilation, this outflow is already accelerated to relativistic bulk speeds causing a significant Doppler shift of the frequency of the annihilation lines. We also show that the subsequent emission of radio synchrotron radiation from the outflow may be caused by only a small fraction of pairs escaping from the annihilation region. We apply this idea to radio and hard X-ray observations of Nova Muscae 1991, thus constraining the properties of the possible outflow from this system. The energy requirements for this source rule out a large contribution of protons to the outflow. We would like to point out that 1E 1740.7–2942 has exhibited annihilation features near 511 keV (e.g. Mandrou et al. 1990), and that there is some evidence of the same in Cyg X-1 (Ling & Wheaton 1989). We are currently working on expanding the arguments presented in this paper to encompass the other two sources (Hannikainen & Kaiser, in preparation).

In Section 2 we discuss under which plasma conditions we can expect Doppler-shifted annihilation lines. Section 3 briefly reviews radio synchrotron emission. The case of Nova Muscae 1991 is investigated in Section 4 and in Section 5 we summarise our results.

## 2 DOPPLER-SHIFTED ANNIHILATION LINES

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### 2.1 Conditions for a strong, narrow annihilation line

The direct annihilation of an electron-positron pair results in the production of two  $\gamma$ -ray photons, each with an energy of 511 keV in the rest-frame of the annihilating particles. In the case of a hot pair plasma the resulting emission line is broadened by the random thermal motion of the pairs (Ramaty & Mészáros 1981). Also, the annihilation of a thermal pair plasma is accompanied by bremsstrahlung from the pairs. The bremsstrahlung emissivity around 511 keV exceeds that of the annihilation process at temperatures above  $\Theta = kT/(m_e c^2) = 3$  (Svensson 1982; Maciołek-Niedźwiecki, Zdziarski & Coppi 1995, hereafter MZC95). Below a temperature of about  $10^6$  K the annihilation proceeds via the formation of positronium leading to a distinctive low-energy wing of the annihilation line (e.g. Longair 1994). Thus in the case of a thermal pair plasma the plasma temperature must lie roughly in the range  $10^6$  K to  $4 \times 10^9$  K for a narrow annihilation line to be observable.

In a plasma, pairs may be produced by various mechanisms. Unless there is a strong external radiation field containing many photons with energies in excess of 511 keV, all of these require the presence of highly energetic electrons and soft seed photons. The electrons upscatter the soft photons beyond the pair creation threshold and thus the plasma starts producing pairs. As a by-product of the pair production, a strong Comptonization spectrum is emitted by the plasma. MZC95 point out that this Comptonization spectrum completely swamps the annihilation line in thermal plasmas. An observable narrow line can only be produced if a large fraction of the pairs escapes from the plasma and has time to cool before annihilating. However, this implies the existence of a rather sharp boundary between a fairly hot pair plasma bathed in an intense radiation field of soft photons and a region virtually devoid of any soft photons. Also, although the pairs escape the plasma, the volume containing the pairs must be confined at least for a time longer than the cooling time. Any expansion would lead to enormously reduced annihilation rates. Although it is certainly possible to construct such geometries, the existence of non-thermal leptons within the plasma allows for a simpler way of producing a narrow annihilation line.

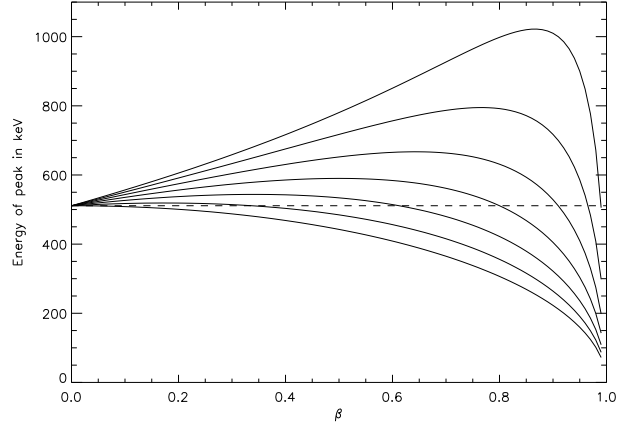
In non-thermal plasmas relativistic electrons or pairs may be injected into the plasma. The injected pairs and those produced in the plasma may cool to sub-relativistic energies and thermalize before annihilating, thus leading to a narrow annihilation line (Lightman & Zdziarski 1987, hereafter LZ87). If the line is strong, it can rise above the Comptonization spectrum and becomes detectable. This requires a high pair yield,  $Y$ , defined as the ratio of the energy converted to pairs and the energy supplied to the plasma. The highest pair yields can be achieved when the plasma is ‘photon-starved’, i.e. when the number of injected relativistic photons strongly exceeds that of the injected soft photons (Zdziarski, Coppi & Lamb 1990). In this case,  $Y \sim 0.25$  and a strong, narrow annihilation line above the Comptonization continuum becomes observable.

We conclude that the observation of a narrow annihilation line most likely indicates a plasma with strong injection of non-thermal electrons or pairs. The injection of leptons into a spherical volume of radius  $R$  is characterised by the compactness (e.g. LZ87)

$$l_e = \frac{L_e \sigma_T}{R m_e c^3}, \quad (1)$$

where  $\sigma_T$  is the Thomson cross-section and  $L_e$  is the power of the electron injection,

$$L_e = \frac{4\pi R^3}{3} m_e c^2 \int Q_1(\gamma) (\gamma - 1) d\gamma. \quad (2)$$



**Figure 1.** Doppler-shift of positron annihilation radiation from relativistically moving material approaching an observer. The dashed line shows the unshifted rest-frame energy of the annihilation line at 511 keV. The solid lines show the energy of the line as function of the velocity of the material as observed at various angles to the line of sight (Equation 3).  $\theta$  is increasing in steps of  $10^\circ$  from  $30^\circ$  (top) to  $90^\circ$  (bottom).

Here,  $Q_1(\gamma)$  is the rate of injection of leptons with Lorentz factor  $\gamma$  per unit volume per unit time per unit  $\gamma$ . If the compactness  $l_e$  can be inferred from the observations of an annihilation line, then Equations (1) and (2) can be used to constrain  $Q_1(\gamma)$ .

### 2.2 Relativistic Doppler-shifts

Any emission of relativistically moving material is Doppler-shifted in its frequency. For material moving with bulk velocity  $v_b = \beta c$  at an angle  $\theta$  to the line of sight to the observer, the observed frequency,  $\nu$ , of radiation emitted at frequency  $\nu'$  in the rest-frame of the material is given as

$$\nu = \frac{\nu'}{\gamma_b (1 \pm \beta \cos \theta)} = \nu' \delta_{\pm}, \quad (3)$$

where  $\gamma_b$  is the Lorentz factor corresponding to the velocity  $\beta$  (e.g. Rybicki & Lightman 1979). The upper signs correspond to material receding along the line of sight to the observer while the lower signs indicate approaching material. From Equation (3) it is clear that radiation of material receding from an observer is always redshifted. However, for approaching material the emission may be blueshifted or redshifted, depending on the combination of  $\beta$  and  $\theta$ . Figure 1 shows this effect for the example of positron annihilation radiation emitted at a rest-frame energy of 511 keV. Any combination of  $\beta$  and  $\theta$  below the dashed line in this figure corresponds to redshifted emission from the approaching material. The range of velocities which result in such a Doppler redshift is largest for angles to the line of sight close to  $90^\circ$ .

For a source with a bipolar outflow with components travelling in opposite directions there will always be one approaching and one receding component. If both components emit a strong annihilation line, we expect to observe two such lines at frequencies  $\nu_-$  and  $\nu_+$ . Assuming the same bulk velocity for both components, Equation (3) can then be solved for the bulk velocity of the components,

$$\gamma_b = \frac{\nu'}{2} \left( \frac{1}{\nu_-} + \frac{1}{\nu_+} \right), \quad (4)$$

and for the angle of the bulk velocity to the line of sight

$$\cos \theta = \frac{1}{\beta} \left( \pm \frac{v'}{\gamma_b v_{\pm}} \mp 1 \right), \quad (5)$$

where again the upper signs correspond to the receding component and the lower signs to the approaching one.

In practice it may be difficult to observe the annihilation line from the receding component as this will be strongly boosted. In fact, the ratio of the line fluxes provides for an independent check on the quantity  $\beta \cos \theta$  as (Rybicki & Lightman 1979)

$$\frac{F_-}{F_+} = \left( \frac{1 + \beta \cos \theta}{1 - \beta \cos \theta} \right)^k, \quad (6)$$

with  $k = 3$  for discrete components and  $k = 2$  for continuous jets. It is usually difficult to determine the line fluxes accurately from observations. This, combined with the ambiguity of the value of  $k$ , implies that the line flux ratio is of limited use.

### 3 RADIO SYNCHROTRON EMISSION AND ABSORPTION

Synchrotron emission arises from relativistic electrons and/or positrons spiralling in a magnetic field. It is usually described by a power law spectrum with  $L_{\nu} \propto \nu^{\alpha}$ . Both the relativistic particles and the magnetic field store energy, but how the total energy is divided between the two cannot be determined from the observed radiation alone. However, it is well known that there is a minimum total energy required to produce a given monochromatic synchrotron luminosity,  $L_{\nu}$ . This is usually expressed in terms of the magnetic field corresponding to this condition

$$B_{\min} = \left[ \frac{3\mu_0 G(\alpha) L_{\nu}}{2V} \right]^{2/7}, \quad (7)$$

where  $V$  is the volume of the emitting region and  $G(\alpha)$  is a numerical constant depending on the slope of the synchrotron spectrum,  $\alpha$ , and on  $\nu_{\min}$  and  $\nu_{\max}$ , the limits of the spectrum. It is usually assumed that  $\nu_{\min} \sim 10$  MHz and  $\nu_{\max} \sim 100$  GHz. Note here that the exact choice for the spectral cut-offs, and particularly the choice for  $\nu_{\max}$ , has very little influence on the value of  $G(\alpha)$  for  $\alpha \sim 0.5 \rightarrow 0.9$ , typical for optically thin synchrotron radiation (e.g. Longair 1994). The energy in the relativistic particles is then given by

$$W_{\text{part}} = \frac{2VB_{\min}^2}{3\mu_0} = Vm_e c^2 \int P(\gamma)(\gamma - 1) d\gamma, \quad (8)$$

where  $P(\gamma)$  is the number of relativistic particles with Lorentz factor  $\gamma$  per unit volume per unit  $\gamma$ . For a given synchrotron luminosity and a known volume of the emission region we can therefore constrain  $P(\gamma)$ . Obviously, this is just an estimate as the distribution of the energy between the relativistic particles and the magnetic field may depart strongly from the minimum energy values. However, such a departure would lead to much higher overall energy requirements.

The estimates presented above implicitly assume that the emission region is optically thin to radio waves. This is not necessarily the case, particularly in the inner, dense regions of the source. For  $P(\gamma) = P_0 \gamma^{-p}$  the optical depth is

$$\tau = F(p) n_0 B_{\min}^{(p+2)/2} v'^{-(p+4)/2} R, \quad (9)$$

where  $F(p)$  is a function of  $p$  only (e.g. Longair 1994) and  $R$  is the typical path length photons have to travel through the emission region. If the magnetic field is tangled on scales significantly smaller than the physical size of the emission region, its energy density obeys  $u_{\text{mag}} \propto V^{-4/3}$ . So for a spherical volume of radius  $R$  and  $V \propto R^3$  we find

$$\tau \propto (R^2 v')^{-(p+4)/2}. \quad (10)$$

### 4 THE CASE OF NOVA MUSCAE

Nova Muscae (GRS 1124–684) was discovered on 1991 January 8 by Granat (Lund & Brandt 1991; Sunyaev 1991) and Ginga (Makino 1991). An extensive monitoring campaign with Granat covering most of January and February 1991 followed this initial discovery (Gil'fanov et al. 1991, hereafter GSC91; Sunyaev et al. 1992; Gil'fanov et al. 1993). During observations on January 20–21, a strong, narrow line near 500 keV was detected. This line had not been noted before and the line flux was observed to increase during the observation within the space of a few hours. Unfortunately, the observations stopped before the line flux decreased again, implying a lifetime of the line emission of at least 10 hours. During subsequent observations on February 1–2 it was not detected. Simultaneously to the strong line near 500 keV, there was also increased emission detected near 200 keV. The spectrum obtained with Granat during 1991 January 20–21 is shown in Figure 2. GSC91 fitted the spectrum with a power-law continuum and two Gaussian line profiles. The lines peak at  $474 \pm 30$  keV and  $194 \pm 13$  keV. The line fluxes are given as  $(6.6 \pm 3.6) \times 10^{-3}$  photons  $\text{s}^{-1} \text{cm}^{-2}$  and  $(1.5 \pm 1.3) \times 10^{-3}$  photons  $\text{s}^{-1} \text{cm}^{-2}$  respectively. The FWHM of the line centred at 474 keV is  $70 \pm 70$  keV.

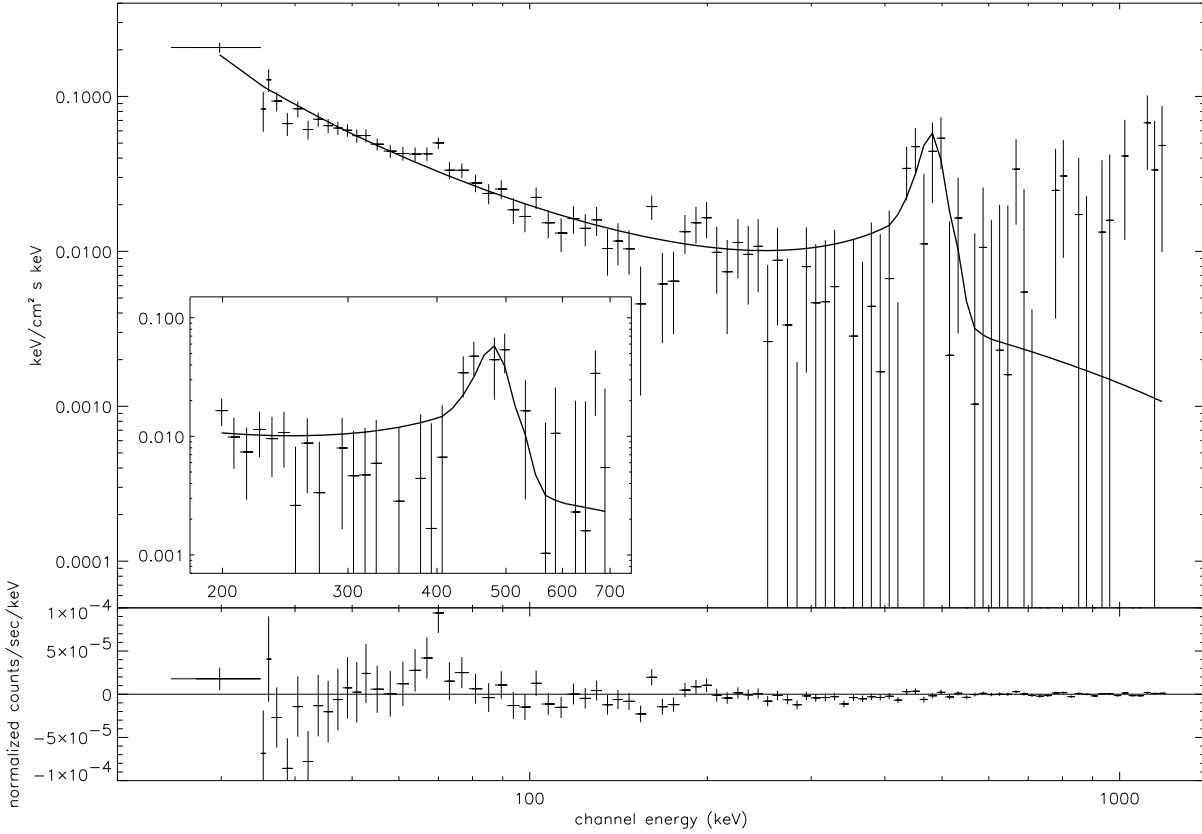
The original discovery also triggered a radio monitoring programme using the Molongolo Observatory Synthesis Telescope (MOST) and the Australia Telescope Compact Array (ATCA) at frequencies ranging from 843 MHz to 8.6 GHz (Kesteven & Turtle 1991; Ball et al. 1995). The campaign started on January 17 and continued into early February. The radio lightcurve at 843 MHz obtained with the MOST is shown in Figure 3. Ball et al. (1995) note four distinct features in the lightcurve. There is a general decay of the radio flux from the very beginning of the programme continuing until about January 22. This is interrupted by a brief flare around January 18 observed with ATCA (not shown in Figure 3). There is another flare observed from January 31 until around February 5. Finally, a short flare was observed by MOST at 843 MHz on January 24 with a measured flux density of 24 mJy. The event lasted only one day. There were no observations at other frequencies.

In the following we will concentrate on the detection of the  $\gamma$ -ray lines on January 21 and the brief radio flare on January 24. We speculate that the same ejection event is responsible for the emission at opposite ends of the electromagnetic spectrum observed on the two days.

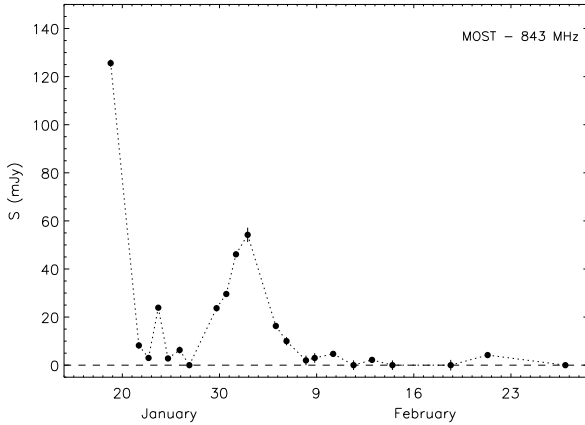
#### 4.1 Constraints from the annihilation line

We assume here that the two  $\gamma$ -ray lines observed in the spectrum of Nova Muscae arise from pair annihilation in a relativistic bipolar outflow from the very centre of the system. In this model, the line at 474 keV is associated with the approaching component while that at 194 keV arises from the receding component.

Using Equations (4) and (5) we then find  $\theta = 60^\circ \pm 7^\circ$  for the angle to the line of sight of the component motion and  $\beta = 0.84 \pm$



**Figure 2.** The best-fit model to the spectrum of Jan 21. The large figure shows the full spectrum from the last third of the Jan 20–21 observation, showing the emergence of the annihilation features. The inset shows the data points around 474 keV used in the fitting procedure (see the text), while the bottom panel shows the residuals of the model to the data in normalised counts per second.



**Figure 3.** MOST 843 MHz lightcurve showing the decay of the initial outburst of January 8 and the two bursts of January 24 and January 31.

0.02 for the bulk velocity of the components. This corresponds to a Lorentz factor of  $\gamma_b = 1.86 \pm 0.12$ . The errors are determined from the uncertainties in the frequency of the line peaks as given by GSC91. With these values we expect the ratio of the line fluxes of the approaching and the receding components to be  $F_-/F_+ =$

$15 \pm 10$  for discrete components and  $F_-/F_+ = 6 \pm 3$  for continuous jets (see Equation 6). The observed line fluxes give  $F_-/F_+ = 4 \pm 6$ . The velocity and angle to the line of sight calculated from the frequencies of the line peaks are consistent with this within the errors. However, the uncertainties are very large.

The companion star in Nova Muscae is tidally distorted by the black hole. The resulting variation in the lightcurve has been modelled by Orosz et al. (1997) who constrain the inclination of the system to  $54^\circ \leq i \leq 65^\circ$ , and also by Shahbaz, Naylor & Charles (1997) who find  $i = 54^{+20}_{-15}$ . It is reasonable to expect that  $i$  is also the inclination angle of the accretion disc around the black hole and that the bipolar outflow moves in a direction perpendicular to this disc. However, note that the jets in GRO J1655-40 appear to be misaligned with respect to the direction perpendicular to the disc (e.g. Orosz & Baylin 1997). With these assumptions we should find  $\theta = i$ , i.e. the angle of the outflow direction to the line of sight is equal to the inclination of the system. Our value for  $\theta$  is fully consistent with this interpretation.

We now take a closer look at the profile of the line centred at 474 keV. The line at 194 keV is too weak to allow any detailed investigation of its profile, and hence we only fit the line at 474 keV for this present study. The FWHM of the line at 474 keV is only 70 keV which implies a pair temperature of only about  $4 \times 10^7$  K at the time of annihilation (Ramaty & Mészáros 1981; GSC91).

The rate of annihilation implied by the line flux is  $\dot{N}_+ \sim 2 \times 10^{43}$  pairs  $\text{s}^{-1}$  for a distance of 5.5 kpc (Orosz et al. 1996).



This enormous rate is sustained for at least 10 hours (Sunyaev et al. 1992). It is therefore very unlikely that this feature at 474 keV arises from a large number of pairs formed practically instantaneously and then slowly annihilating away. This would imply a short-lived flash of annihilation photons with a fast, exponential decay contrary to the lifetime of the annihilation features of at least 10 hours. A more promising approach is to assume that the pair producing plasma is in equilibrium, i.e. the annihilation losses are balanced by pair creation. MZC95 failed to fit the line with such a model assuming a thermal plasma with strong pair escape. They also tried a model with injection of non-thermal electrons based on the work of LZ87. Again, the fit was poor. However, they did not take into account a possible Doppler-redshift of the line.

After correcting the spectrum for the redshift derived above, we attempted a fit essentially identical to that of MZC95. We used the model NTEEA within the XSPEC package which is an implementation of the model developed in LZ87. We disabled any contribution to the spectrum by reflection off the disc. The temperature of the black body providing the soft seed photons for the pair creation process was set to 1 keV which gives a reasonable fit to the low energy spectrum of Nova Muscae (see MZC95). Further, we assumed that there was no thermal heating of the plasma, no escape of pairs from the source and that the optical depth due to protons was zero. The energy spectrum of the injected relativistic electrons was described by  $Q_1 = Q_0 \gamma^{-2.2}$ , extending from  $\gamma_{\min} = 1$  to  $\gamma_{\max} = 1000$ . We have chosen the slope of the power law to be equal to that of the radio emission (see Section 4.2). Variation of this parameter as well as changing  $\gamma_{\min}$  and  $\gamma_{\max}$  was found to cause only minor differences in the result. Finally, the model assumes that the plasma is contained within a spherical volume. The radius of this we set to  $R = 2 \times 10^5$  m corresponding to the Schwarzschild radius of a black hole of mass  $6 M_{\odot}$ . This is the minimum conceivable size of the annihilation region. In any case, the exact value of  $R$  is only important for the determination of energy losses due to Coulomb and bremsstrahlung processes. It does not significantly influence the model fit of the annihilation line. The only free parameters in this fit were the compactness of the non-thermal electron injection,  $l_e$ , and the compactness of injected soft photons,  $l_s$ . The latter is defined to be analogous to  $l_e$  with  $L_e$  in Equation (1) replaced by the luminosity of the soft photon injection. As we were only interested in fitting the annihilation line at 474 keV, we only used data points in the range 195–699 keV. We also excluded all negative flux measurements within this range which resulted in 23 data points to be fitted.

Figure 2 shows our best fit with a reduced  $\chi^2$ -value of 1.35 (for 84 d.o.f). The free parameters,  $l_e \sim 3000$  and  $l_s \sim 50$ , imply a strongly photon-starved plasma. The parameters are not well constrained as under these conditions the pair yield does not depend strongly on their exact values (e.g. LZ87). We find a lower limit for  $l_e$  of about 100, below which the pair yield is too small to give a good fit. Despite these uncertainties, the correction of the data for a Doppler-redshift clearly makes a reasonable fit of the annihilation line possible.

Re-arranging Equation (1) yields

$$L_e = \frac{R m_e c^3 l_e}{\sigma_T}. \quad (11)$$

Substituting in our lower limits for  $R$  and  $l_e$ , we find  $L_e \geq 7 \times 10^{30}$  W. From Equation (2) it follows that  $Q_0 = 9 \times 10^{26} \text{ m}^{-3} \text{ s}^{-1}$  for this lower limit. The rate at which relativistic electrons are injected is then  $N_{\text{inj}} = 3 \times 10^{43} \text{ particles s}^{-1}$ . This is comparable to the observed annihilation rate of  $2 \times 10^{43} \text{ particles s}^{-1}$ .

## 4.2 Constraints from the radio emission

The radio flare occurred on 1991 January 24, about three days after the observation of the annihilation lines. If this emission arose from the same material that was responsible for the annihilation features at the very centre of the source, then these ejection components were by then located roughly  $7 \times 10^{13}$  m further out. This assumes that the components did not decelerate. When resolved in the radio, the ejections of X-ray transients are quite collimated (e.g. Mirabel & Rodríguez 1994; Hjellming & Rupen 1995). In order to estimate the size of the radio-emitting region, we assume a half-opening angle of the ejection of  $1^\circ$ . This implies a radius of  $10^{12}$  m for a spherical component. The measured flux density was 23.9 mJy at 843 MHz which we associate entirely with the approaching component. For the values found in Section 4.1 for the bulk velocity,  $\beta = 0.84$ , and the angle to the line of sight,  $\theta = 60^\circ$ , this converts to 29.9 mJy emitted at 909 MHz in the rest frame of the approaching component. This assumes a discrete component rather than a continuous jet. We have no information on the slope of the radio spectrum for 24 January. Therefore, we adopted a spectral index of  $\alpha = -0.6$  as derived from the multi-frequency observations of the earlier flares. This implies that  $P(\gamma) = P_0 \gamma^{-2.2}$ . For a distance to the source of 5.5 kpc (Orosz et al. 1996) and using Equation (7), we find the magnetic field strength corresponding to minimum energy conditions to be  $B_{\min} = 0.015$  mT. Using Equation (8) this implies  $W_{\text{part}} = 5 \times 10^{32}$  J and  $P_0 = 8 \times 10^8 \text{ m}^{-3}$ . The number of relativistic particles in the emitting volume is  $N_{\text{rel}} = 2 \times 10^{44}$ .

Adopting the radius of the emission region at the time of the observation as a scale radius  $R_0 = 10^{12}$  m, Equation (9) for the optical depth at  $\nu' = 909$  MHz yields

$$\tau \sim 0.1 \left( \frac{R}{R_0} \right)^{-6.2}. \quad (12)$$

## 4.3 Implications of a bipolar flow

The annihilation feature observed persists for at least 10 hours (Sunyaev et al. 1992). The production of an outflow must have lasted at least for that length of time. In the case of a shorter ejection event the annihilation rate would decrease dramatically as the ejected material travels outwards and expands. Of course, the annihilation could also proceed in a region close to the centre of the source without moving outwards. In this case, the displacement of the line at 474 keV could be explained as arising from gravitational redshift. This requires the annihilation region to be inside about 7 Schwarzschild radii of the  $6 M_{\odot}$  black hole. However, in this case it is not clear what causes the second, simultaneous line at 194 keV.

An entirely different explanation for the line at 474 keV is given by GSC91 and also by Martín et al. (1994). This involves the emission of  $\gamma$ -ray photons of energy 468 keV during the formation of  ${}^7\text{Li}$  close to the black hole. This is supported by the observation of optical lithium lines. However, GSC91 point out that the proximity of the lithium production region to the black hole should result in a strong rotational broadening of the line. Furthermore, the secondary line at 194 keV is again not explained in this scenario.

Misra & Melia (1993) presented a model for electron-positron pair jets to explain the annihilation line observed in the spectrum of the Galactic centre source 1E 1740.7-2942. Their model is based on a radiative acceleration mechanism for the jets. The great majority of pairs annihilate within the acceleration zone with a large variation in the thermal pair temperature. This leads to the formation of quite a broad line. Also, as mentioned before, a model with

purely thermal pairs is unable to account for the annihilation line in the case of Nova Muscae (MZC95). In the model presented here we argue that the bulk of the outflow containing the pairs is already accelerated when they annihilate, thus explaining the redshifts of the two observed lines. The velocity of the outflow is then  $0.84c$ , while the radiative acceleration allows only for a terminal velocity of about  $0.7c$ . Because of this, the acceleration of the outflow must, at least partly, be due to some other mechanism(s).

The energy required to drive the outflows is enormous. As the relativistic electrons necessary for pair production are highly relativistic, their mass in the rest frame of the outflow material is given by  $\gamma m_e$ . Therefore, the total kinetic power of the relativistic electrons, as measured in the source rest frame, injected into the outflow can be approximated as

$$\dot{E}_{\text{kin}} = V Q_0 m_e c^2 (\gamma_b - 1) \int \gamma^{1-p} d\gamma \sim 6 \times 10^{31} \text{ W}. \quad (13)$$

In this estimate we have used the limiting values for the electron compactness,  $l_e = 100$ , and the size of the emission region,  $R = 2 \times 10^5 \text{ m}$ . Any increase in these parameters will also cause the energy estimate to rise. Therefore, the lower limit on  $\dot{E}_{\text{kin}}$  corresponds already to about 80% of the Eddington luminosity of a  $6 M_\odot$  black hole. Balance of electrical charge requires the presence of positively charged particles in the outflow. If these are protons with negligible thermal energy but travelling at the necessary bulk velocity, then another  $4 \times 10^{33} \text{ W}$  in kinetic energy are required. This is more than a factor 50 more than the Eddington luminosity. This energy injection into the outflow has to be sustained for more than 10 hours and thus makes a large proton content in the jet very unlikely.

The only alternative is then that from the very beginning of the ejection the outflow material in the annihilation region consists of virtually a pure pair plasma. This removes the requirement of relatively inefficient pair production from relativistic electrons. The pairs must be injected into the relativistic bulk flow with a relativistic velocity distribution to explain the strength of the annihilation line (MCZ95), the cooling within the outflow and then annihilation at a rate of  $2 \times 10^{43} \text{ s}^{-1}$ . In this case, the required kinetic power is about  $6 \times 10^{30} \text{ W}$ , or 8% of the Eddington luminosity.

Assuming that the outflows consist entirely of pairs, at least  $7 \times 10^{47}$  pairs are injected into the outflow approaching us. Most of these annihilate but a small fraction may escape the annihilation region. If the radio flare discussed above is associated with the annihilation line feature and the radio-emitting region only contains the relativistic pairs required by minimum energy arguments, then only one in 7000 pairs need escape. In the model of Misra & Melia (1993), roughly 10% of all pairs escape, which would imply a large thermal population underlying the radio-emitting relativistic pairs. Nevertheless, the kinetic energy of this thermal population is, at  $3 \times 10^{29} \text{ J}$ , small compared to the kinetic energy of  $10^{33} \text{ J}$  of the relativistic and therefore heavy radio-emitting particles. In any case, the energy required to explain the radio observations is at most only a fraction of 5% of the originally injected energy. Thus the radio emission observed in X-ray transients may represent only an almost negligible fraction of the energy initially available to the outflow.

The time between the detection of the annihilation line features from Nova Muscae and the first observations of a radio flare is roughly three days. During this time, a number of observations at various frequencies showed no sign of enhanced radio emission (Ball et al. 1995). This would argue against a connection between the two events. However, Equation (12) shows that the out-

flow became optically thin to emission around 1 GHz only when  $R \sim 0.7R_0$ . For a constant opening angle of the outflows as assumed throughout, this implies that radio observations would have detected this flare only two days after its start at the earliest.

The existence of highly relativistic electrons far out from the centre of the source implies a secondary acceleration mechanism. The annihilation line at 474 keV is consistent with a pair temperature of only 5 keV. Therefore the escaping pairs are sub-relativistic and must be re-accelerated to explain the radio emission. One possibility is the existence of internal shocks within the outflow (e.g. Kaiser, Sunyaev & Spruit 2000). The duration of the outflow production is easily long enough to allow for variations in the outflow speed which may lead to the formation of such shocks. Alternatively, the particles may be re-accelerated at a working surface at the end of the flow, as is the case in many extragalactic jet sources.

## 5 CONCLUSIONS

From the above discussion it is likely that Nova Muscae underwent a number of bursts resulting in relativistic outflows. The production of these outflows would then always be accompanied by strong annihilation line emission followed by radio synchrotron emission a few days later. Here we are assuming that the radio emission arises in jets. Unfortunately, only one of the rather minor outbursts of Nova Muscae in 1991 was covered by both  $\gamma$ -ray and radio observations. The strongest outburst leading to the first detection of the system on 1991 January 8 was observed with insufficient energy resolution to establish the presence of an annihilation line. Subsequent high-resolution observations on January 9 did not detect any lines. There were two more minor radio bursts. One of them occurred on January 18 and a longer burst started around January 31 (Ball et al. 1995). If the three days' delay between the appearance of the annihilation lines and the start of the radio emission is typical, then the two radio flares should have been preceded by annihilation lines on January 15 and around January 28 respectively. There were no  $\gamma$ -ray observations during the period from January 11 until January 16 and from January 22 until February 1 (GSC91). The non-detections of January 9 and January 16 may be taken as evidence that the outflow production, when it occurs, is rather short-lived.

If it is true that the annihilation features observed originate from accelerated plasma, then protons as a contributing factor to the matter in the plasma are ruled out. The scenario we have discussed favors a pair plasma — even if only a tiny fraction of the pairs survives, this is sufficient to produce the observed radio emission. Furthermore, the detection of Doppler-shifted annihilation lines is a direct method, independent of uncertainties arising from other observational parameters such as fluxes, by which to directly measure jet speeds.

However, to confirm the outflow scenario linking  $\gamma$ -ray line observations with radio emission, further detailed, time-resolved observations are needed. The spectral and temporal resolution of INTEGRAL will enable the detection and follow the evolution of possible annihilation features in other jet sources. This will prove extremely valuable in the case of, for example, GRS 1915+105 which is heavily obscured at visible wavelengths. In addition, this study was applied to Nova Muscae which is a transient, and hence it will be interesting to observe the behaviour of permanent jet sources, such as 1E 1740.7–2942, from which an annihilation line has already been detected.

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